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# Skew Quadrupole in RHIC Dipole Magnets at High Fields

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***Abstract*— In the RHIC arc dipoles, the center of the cold mass lies above the center of the cryostat. At the maximum design field, the magnetic flux lines leak through the yoke to the asymmetrically located cryostat, which provides an additional return path. This introduces a systematic top-bottom asymmetry leading to a skew quadrupole term at high fields. A similar asymmetry is also created by any difference in weights of the upper and the lower yoke halves. Data from measurements of several RHIC dipoles are presented to study this effect. In the current production series of the RHIC dipoles, an attempt is made to compensate the effect of the cryostat by an asymmetry in the iron yoke. Seven dipoles with this type of yoke have been cold tested, and show a reduced saturation in the skew quadrupole term, as expected.**

## I. Introduction

The cold mass in the RHIC arc dipoles is placed on insulating support posts in a cryostat made of low carbon steel. In order to minimize the heat load, the support posts are made as long as possible. This places the center of the cold mass above the center of the cryostat, as shown in Fig.1. Such an asymmetric placement of the cold mass has practically no effect on the magnetic field quality at low fields since the yoke provides adequate shielding. At the maximum operating central field of 3.46 Tesla at 5.1 kA, the iron yoke is saturated. The magnetic flux lines at such high fields leak through the yoke to the asymmetrically located cryostat, which provides an additional return path. A systematic top-bottom asymmetry is thus introduced, leading to a current dependent skew quadrupole term at high fields. In addition, the weights of the upper and the lower halves of the horizontally split yoke may not be exactly equal. This would also influence the current dependence of the skew quadrupole term.

In this paper we present the data on variation of the skew quadrupole term with current in the RHIC arc dipoles that have been cold tested at 4.6K. Some attempts to minimize the current dependence of skew quadrupole in the present production series of the arc dipoles are also described.

## II. Current Dependence of the Skew Quadrupole Term

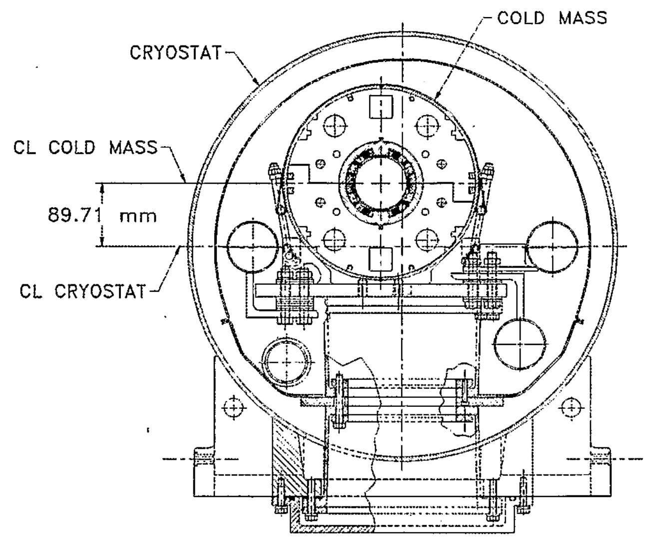


Fig. 1. A cross section of the RHIC arc dipole showing the asymmetrically located cold mass in the cryostat. The left-right asymmetry seen is due to sagitta of the magnet, and varies along the axis. The cross section shown is at the axial center.

The field quality in the RHIC magnets is expressed in terms of the normal and skew harmonic coefficients, $b_n$ and $a_n$ in dimensionless "units" defined by the following multipole expansion

$$B_y + iB_x = 10^{-4} \times B_0 \sum_{n=0}^{n=\infty} (b_n + ia_n)[(x+iy)/R]^n$$

where $x$ and $y$ are the horizontal and vertical coordinates, $B_0$ is the dipole field strength and $R$ is a "reference radius", chosen as 2.5 cm for the RHIC arc dipoles. This reference radius is (5/8) of the coil inner radius, which is 4 cm in these dipoles. In the above expansion, it should be noted that the normal and skew quadrupole terms are denoted by $b_1$ and $a_1$ respectively. We shall use the notation $a_1$ in this paper to denote the skew quadrupole term.

The field quality in all the RHIC dipoles is measured at room temperature using a one meter long rotating coil system[1]. The integral harmonics are determined from an axial scan of the magnet in one meter steps. The first 30 dipoles were also measured cold with the rotating coil system. Subsequently, only about 10% of the dipoles are tested cold.

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The field measurements consist of axial scans at 660A (injection), 1450A (transition) and 5000A (storage). In addition, the complete current dependence from 50A to 6000A is studied at one location in the center of the magnet.

The current dependence of the skew quadrupole term measured in the axial center of two of the RHIC dipoles is shown in Fig. 2. In order to facilitate comparison between the two magnets, the geometric skew quadrupole term is removed by subtracting the value at 1450A. The possible sources leading to variation of $a_1$ with current in the SSC dipoles are discussed in an earlier paper [2]. In the case of the RHIC dipoles, the primary source of this variation is the asymmetrically located cold mass in the cryostat, as discussed earlier. The change in the value of $a_1$ between 1450A and 5000A will be referred to as "$a_1$ saturation" since the major source of this change is the saturation of the iron yoke. The skew quadrupole contribution at 1450A from superconductor magnetization is less than 0.1 unit in all the magnets.

## III. MAGNET TO MAGNET VARIATION IN $a_1$ SATURATION

The two magnets shown in Fig. 2 exhibit the largest (DRG125, filled boxes) and among the smallest (DRG113, solid line) skew quadrupole saturation. Based on the effect of the cryostat alone, all magnets are expected to show nearly the same current dependence in $a_1$. Such large magnet to magnet variations lead to uncertainties in predicting the values at high fields based on warm measurements alone.

The magnet to magnet variations can arise due to differences in the iron weights in the upper and the lower yoke halves. In the case of the SSC dipole prototypes, a good correlation was found between the top-bottom yoke weight asymmetry and the $a_1$ saturation [2]. Such a correlation is to be expected, because an asymmetry in the iron weights could either add to or cancel the effect of the cryostat, depending on the sign of the asymmetry.

In the case of the RHIC dipoles, the upper and the lower iron yoke weights are available in three different sections. We calculated the values of the skew harmonic terms integrated over each of these three sections in a magnet by appropriately summing the values measured in axial scans. Using axial scans at 1450A and 5000A, we can calculate the $a_1$ saturation in each of the three sections of a magnet.

Fig.3 shows the correlation between the yoke weight asymmetry and $a_1$ saturation in all the dipoles tested so far. The yoke weight asymmetry is defined as

$$\text{asymmetry} = \frac{\text{weight of Top part - weight of Bottom part}}{\text{Average weight of Top and Bottom parts}}$$

There are a total of 38 magnets in the plot shown in Fig.3, for a total of 114 (=3x38) points in the plot. A good correlation is seen between the yoke weight asymmetry and the saturation in skew quadrupole, as expected. The solid line shows a linear fit to the data points. A few of the data points are seen to lie away from the line. This lack of correlation in certain sections of a few magnets could be due to incorrect recording of the yoke weight. The linear fit shown excludes such data points (seven points in all, belonging to six different magnets). The linear fit gives an $a_1$ saturation of −1.9 units for zero asymmetry in yoke weight, in good agreement with

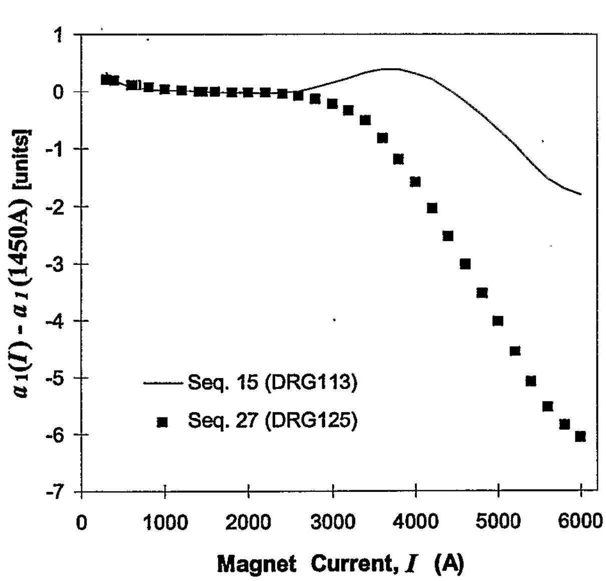


Fig. 2. Current dependence of the skew quadrupole term in the dipoles DRG113 and DRG125. The magnitude of change between low currents and 5000A is the largest in DRG125 and is relatively small in DRG113.

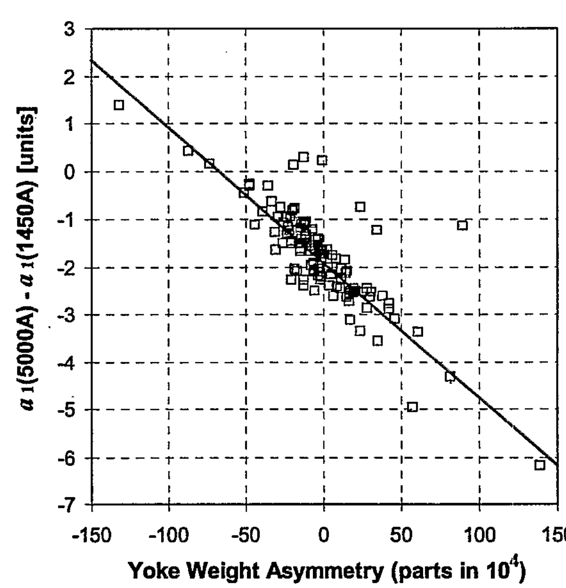


Fig. 3. Correlation between the yoke weight asymmetry and the saturation in the skew quadrupole term. There are three data points for each magnet corresponding to the three sections of the yoke blocks for which the weights are known.

theoretically calculated value of −2.0 units. Furthermore, the slope of the line gives a change of −2.8 units in $a_1$ saturation for 1% asymmetry in the iron yoke weight. This is also consistent with calculations. The calculated current dependence of the skew quadrupole term is shown in Fig. 4 for various values of top-bottom weight asymmetry. The calculated curves are similar to the measured current dependences shown in Fig. 2.

## IV. CONTROL OF $a_1$ SATURATION

As seen from Fig.3, there is considerable magnet to magnet variation in $a_1$ saturation. This variation is a result of asymmetry in the top and bottom yoke weights. The production specifications for the RHIC dipoles specify that the total weight of the yoke be held constant within ±2 kg. The total yoke weight is approximately 2764kg. Ideally, the weights of the yoke halves should be controlled with little magnet to magnet variation. However, such a requirement is difficult to fulfill in practice. Since the yoke laminations are 6.35 mm thick with a tolerance of 0.25 mm, the weights of the yoke packs are expected to differ somewhat.

On the other hand, the systematic value of skew quadrupole measured at low fields in the RHIC production dipoles is close to zero. If the upper and the lower yoke blocks are exactly matched in weight, this would imply a systematic $a_1$ of −1.9 units at 5000A due to the cryostat. It is possible to reduce this systematic $a_1$ at high fields by counteracting the asymmetry of the cryostat by some other means. Various possible means to achieve this are suggested in [3].

The control of $a_1$ saturation essentially requires that additional iron be available in the bottom half of the yoke compared to the top half. We have utilized the natural variations in the weights of the iron yoke blocks to achieve this without incurring any additional cost in the production. In the dipoles now under production at the Northrop-Grumman Corporation, the yoke blocks are assigned in such a way that the heavier blocks are used for the bottom half and the lighter ones for the top half. A top-bottom weight difference of 0.5% is targeted to counteract the −1.9 units of systematic $a_1$ saturation.

Fig. 5 shows the asymmetry in the total upper and the lower yoke weights in all the dipoles delivered so far. The current scheme of yoke blocks assignment was implemented starting with dipole sequence number 63. For dipoles 1 through 62, no attempt was made to control the upper and the lower yoke weights separately. As can be seen from Fig. 5, most magnets in this group had a positive asymmetry, which only added to the effect from the cryostat. For dipoles numbered 63 onwards, it is attempted to make the lower half of the yoke heavier than the top half by approximately 1%. This is reflected in the negative values of asymmetry in Fig. 5 for sequence number 63 and higher. The additional iron on the bottom is expected to counteract the effect of the cryostat proximity on the top.

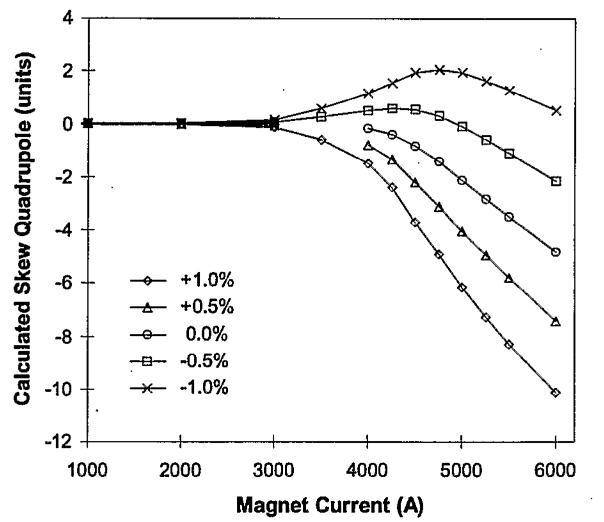


Fig. 4. The calculated current dependence of skew quadrupole term for various values of the asymmetry between the top and the bottom halves of the yoke.

The integral values of $a_1$ in the magnets were obtained by summing the fields measured in the axial scans. The saturation of integral $a_1$ was calculated using the integral values from the axial scans at 1450A and 5000A. The correlation between the integral $a_1$ saturation and the asymmetry in the total upper and the lower weights is shown in Fig. 6 for both the intial magnets (open boxes), and the current production (filled boxes). Once again, the correlation with iron weights can be seen to hold for most of the magnets. The solid line shows a linear fit to data. Some of the points do not fall close to the line. It should be noted that most of these points belong to the same magnets that did not show a good correlation in Fig. 3.

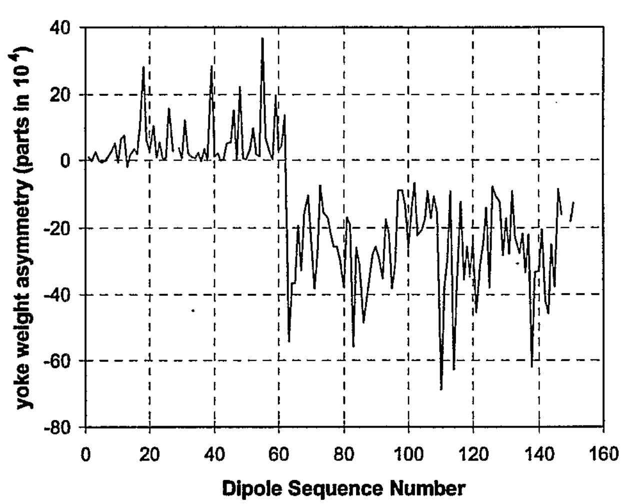


Fig. 5. The asymmetry in the weights of the upper and the lower yoke halves in the RHIC arc dipoles. Starting with magnet sequence number 63, the lower yoke half was made heavier than the top half.

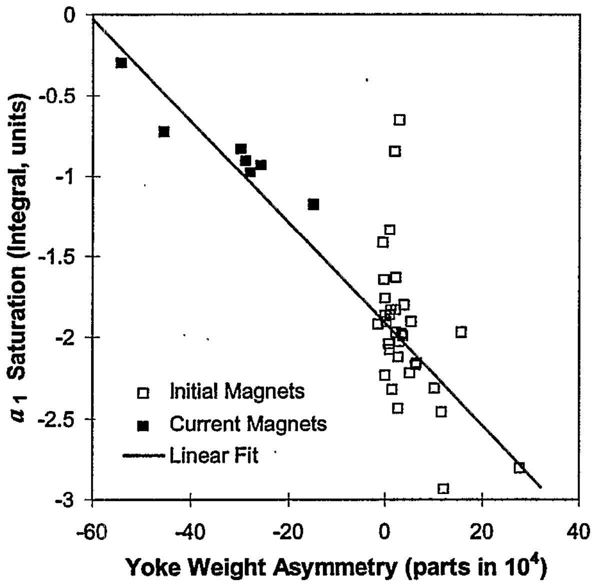


Fig. 6 Correlation between the integral $a_1$ saturation and the asymmetry in the total weights of the upper and the lower yoke halves.

It is clear from Figs. 5 and 6 that the magnets in the new scheme (production sequence 63 and higher) have a negative top-bottom asymmetry in yoke weight on an average. The saturation in $a_1$ is also correspondingly lower. The average $a_1$ saturation in the magnets 1 through 62 (cold data in 33 magnets) is $-1.95$ units, whereas the corresponding average for the magnets 63 onwards (cold data in 7 magnets) is only $-0.83$ units. Thus, a reduction of about 1.1 unit in $a_1$ saturation has been achieved.

## V. Conclusions

A systematic change in the skew quadrupole is introduced in the RHIC dipoles at high fields by the asymmetrically placed cryostat. The variation in saturation of skew quadrupole term, $a_1$, has been seen to be well correlated with the top-bottom asymmetry in the iron yoke weight. The saturation of $a_1$ has been reduced by nearly a factor of 2 by selectively using the heavier yoke packs for the bottom half of the yoke. The scheme takes advantage of the natural variation in the weights, and assigns the heavier packs to the lower half. In other words, the reduction in $a_1$ saturation has been achieved without any additional cost. Furthermore, the good correlation between yoke weight asymmetry and $a_1$ saturation can be used to accurately predict the skew quadrupole term at high fields in the RHIC dipoles based on warm measurements.

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